ATTACHMENT 9 to JAFP-08-0067

**Entergy Nuclear Operations, Inc.
James A. FitzPatrick Nuclear Power Plant**

**NEDO-30799, "James A. FitzPatrick Nuclear Power Station
Feedwater Nozzle Fracture Mechanics Analysis
To Show Compliance with NUREG-0619"
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(Non-proprietary Version)**

ATTACHMENT 9 to JAFP-08-0067 CONTENTS

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GENERAL ELECTRIC COMPANY

JAMES A. FITZPATRICK NUCLEAR POWER STATION

FEEDWATER NOZZLE FRACTURE MECHANICS ANALYSIS

TO SHOW COMPLIANCE WITH NUREG-0619

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ABSTRACT

This report provides a plant specific fracture mechanics assessment of
the FitzPatrick feedwater nozzle with the existing low flow feedwater controller
to show compliance with NUREG-0619 and NRC Generic Letter 81-11, dated
February 20, 1981. The evaluation was based upon the plant operating history
and feedwater system operational data supplied by the New York Power Authority
(NYPA). The evaluation considered an initial crack depth of 0.25 inch as
specified in NUREG-0619. The results show that stress cycling from conserva-
tive temperature and flow profiles, when added to those resulting from other
crack growth phenomena, such as startup and shutdown cycles, do not result in
the growth of an initial 0.25-in. crack to greater than 1 inch during the
remaining life of the plant. Therefore, the existing low flow feedwater con-
troller complies with NUREG-0619 as amended by NRC Generic Letter 81-11.

1. INTRODUCTION

This report provides a plant specific feedwater nozzle fracture mechanics assessment based on the existing James A. FitzPatrick Nuclear Power Plant (hereafter called FitzPatrick) low flow feedwater controller in conjunction with plant operating history. This is in response to the Nuclear Regulatory Commission (NRC) requirements regarding feedwater nozzle crack growth. The results of this analysis meet the requirements of NRC Generic Letter 81-11 which states that a fracture mechanics evaluation must predict an end-of-design-life crack depth of 1 inch or less. Therefore, a new low flow feedwater controller need not be installed.

1.1 BACKGROUND

The GE feedwater nozzle final report (Reference 1) recommended design and operational changes to minimize both the probability of crack initiation and rate of crack growth in feedwater nozzles. The low flow feedwater controller discussed in Reference 1 would not significantly reduce the probability of crack initiation but would reduce crack growth. The NRC (NUREG-0619) accepted the General Electric recommendation (Reference 1) and required that operating reactors install a low flow feedwater controller with the characteristics described in Reference 1 and reroute the Reactor Water Cleanup System (RWCU) flow to all of the feedwater lines. The low flow controller required above must meet strict requirements specified in Subsection 3.4.4.3 of Reference 1. The NRC later clarified its position in Generic Letter 81-11, stating that plant specific analyses may be performed to justify not implementing such modifications.

With respect to low flow feedwater controller installation assessment, feedwater nozzle crack growth analysis is required for FitzPatrick. In order to calculate the feedwater nozzle crack growth, the thermal cycling of the fluid in the feedwater nozzle needed to be determined. For the feedwater line without RWCU return, the fluid temperature in the feedwater nozzle is essentially the same as the feedwater fluid temperature just downstream of the last

feedwater heater. However, for the case of the hot RWCU return flow to the vessel through the feedwater line, the fluid temperature in the feedwater nozzle is not measured directly. Therefore, an energy balance of the two merging flows (i.e., feedwater and RWCU) needs to be made. The total RWCU flow is approximately   of rated feedwater flow. Therefore, feedwater flow variations at low feedwater temperatures and low feedwater flows can cause large temperature cycling of the fluid in the feedwater nozzles.

From the time that the feedwater nozzles were machined (clad removal, December 1978) to the first startup of 1984 (March 1984), all startups and shutdowns were performed with the low flow controller in the manual mode. All subsequent startups and shutdowns were or will be performed under automatic low flow control. A different thermal cycle definition was used for each period.

1.2 OBJECTIVE

This report provides a plant specific fracture mechanics assessment of the FitzPatrick feedwater nozzles to show compliance of the existing low flow feedwater controller with the requirements of NUREG-0619 as amended by Generic Letter 81-11, dated February 20, 1981. The purpose of this analysis is to determine whether stress cycling from conservative controller temperature and flow fluctuations (with the existing low flow feedwater controller), when added to those resulting from the other crack growth phenomena (such as startup and shutdown cycles), will result in crack growth to 1 inch or less during a 40-yr plant life. The evaluation will consider an initial crack depth of 0.25 inch as specified in NUREG-0619.

1.3 TECHNICAL APPROACH

This analysis evaluates the crack growth for both the "hot nozzles" with RWCU injection and the "cold nozzles" without RWCU injection. Although the RWCU System has not been rerouted, an additional analysis was done assuming RWCU reroute in order that the effect of rerouting the RWCU System might be evaluated. After rerouting the RWCU, all four feedwater nozzles would have the same flow and temperature. In this report, such a condition is termed "average nozzle."

1.3.1 Feedwater Flow Cycling

The cycling of the feedwater flow was observed from the plant recorder strip charts for the startup event of March 14, 1984 (Reference 2). The feedwater flow cycling from this event was used for all startup/shutdown and scram events as described in subsection 1.3.2.

1.3.2 Thermal Cycling

The calculated thermal cycling of the fluid in the feedwater nozzle was evaluated for each of the specific startup, shutdown and scram events based on the feedwater flow cycling cited above. A total of   was recorded for FitzPatrick from   (Reference 2). For the calculations of the feedwater nozzle crack growth, the number of thermal cycles per event, as determined from strip charts, and the event history were assumed to be repeated for the remainder of the plant life. Therefore, a total of   events was assumed to take place over the 40-yr plant life.

1.3.3 Crack Growth

To evaluate the crack growth, thermal and pressure stress analyses were conducted using the finite element computer code ANSYS (Reference 3). The location of the peak combined thermal and pressure stress was determined and crack growth was calculated using a crack growth computer code. Two different crack growth relationships were used with this code. The first is a correlation which represents the best-fit to actual PWR and BWR data. The second represents the 1980 ASME Section XI Code Curves.

2. SUMMARY

Application of both crack growth rate relationships resulted in a crack growth within the acceptance criterion of 1 inch or less for a 40-yr plant life. The best-fit crack growth relationship results in a maximum end-of-life crack depth of   , whereas the ASME Section XI crack growth relationship results in a   depth.

Therefore, the existing FitzPatrick low flow feedwater controller is in compliance with NUREG-0619, as amended by NRC Generic Letter 81-11, by meeting the requirement of an end-of-life crack size of 1 inch or less.

Assuming RWCU reroute at the beginning of plant life, the best fit crack growth relationship results in an end-of-life crack depth of   . The ASME Section XI crack growth relationship results in a   depth.

Because the requirements of NUREG-0619, as amended by NRC Generic Letter 81-11, are met without RWCU reroute and because it is shown that RWCU reroute has minimal effect on crack growth, it is recommended that the RWCU System not be rerouted for the purpose of reducing crack growth.

3. THERMAL CYCLE DEFINITION

Each thermal cycle definition presents the number of cycles at a given temperature differential. A single cycle is defined when the nozzle fluid temperature, initially at some value T_0, changes to some other value T_1 and then returns to T_0.

Table 3-1

AUTOMATIC LOW FLOW CONTROL THERMAL CYCLE
DEFINITION; NO REROUTE, RWCU INJECTION LINE
(HOT NOZZLE)

Table 3-2

AUTOMATIC LOW FLOW CONTROL THERMAL CYCLE
DEFINITION; NO REROUTE, NON-RWCU INJECTION LINE
(COLD NOZZLE)

Table 3-3

AUTOMATIC LOW FLOW CONTROL THERMAL
CYCLE DEFINITION; REROUTE
(AVERAGE NOZZLE)

Figure 3-1. Manual Low Flow Control Startup/Shutdown Cycles

4. THERMAL ANALYSIS

The finite element computer code ANSYS (Reference 3) was used to develop an axisymmetric model which simulated the FitzPatrick feedwater nozzle. The isoparametric heat conduction element STIF 55 was used. The model was developed using the nozzle configuration shown in Figure 4-1 (References 4 and 5). The same model with an isoparametric stress element was subsequently used for the stress analysis. Further discussion of the model configuration is included in Section 5.

The heat transfer coefficients were taken from Reference 1. That report provides overall heat transfer coefficients for different thermal sleeve configurations. The coefficients for this analysis represent a triple thermal sleeve sparger with Seal No. 1 failed, as shown in Figure 4-2. The use of this overall heat transfer coefficient
                in the finite element analysis. These heat transfer coefficients with the appropriate temperature boundary conditions are shown superimposed upon a drawing of the finite element model in Figure 4-3.

The initiation of feedwater flow was modeled by varying all of the temperatures,   , from 550°F down to the temperature indicated in Figure 4-3, over a   interval. The temperatures were maintained at this level until steady-state conditions were reached. The   was used rather than   , since it is realistic and assures numerical stability. Subsequent evaluation showed that   conditions induce the most limiting thermal stresses with respect to crack growth.

Figure 4-1. Nozzle Configuration

Figure 4-2. Triple Thermal Sleeve Sparger
(Seal No. 1 Failed)

Figure 4-3. Thermal Boundary Conditions

5. THERMAL AND PRESSURE STRESSES

The results of the thermal analysis are applied to the previously mentioned finite element model to determine the thermal stresses. Isoparametric Stress Element STIF 42 is used in the stress analysis. The nozzle was modeled by an axisymmetric finite element mesh with the vessel being represented as a spherical shell. This is a common approximation used in the stress analysis of a three-dimensional nozzle configuration in a cylindrical shell. This is adequate for thermal stresses but pressure stresses require a scaling factor based on a three-dimensional analysis. The lengths of the nozzle safe end and pressure vessel section are each modeled to at least 2.5 $\sqrt{rt}$, where r is the radius and t is the thickness of the nozzle. This is done to assure that end effects do not influence the stresses in the nozzle corner.

Stresses are evaluated during several time intervals, but the peak stresses occur during   conditions. The peak thermal stress on the inside surface is   , as shown in Figure 5-1 and Table 5-1. The stresses which developed from   are linearly scaled to the ΔT described in the thermal cycle diagram definition (Section 3). The scaled stresses are subsequently used in the crack growth analysis.

Pressure stresses for the case of a 1000-psi vessel pressure are also calculated; however, these stresses require application of a scaling factor. This is necessary because of the limitation of modeling a three-dimensional component with a two-dimensional axisymmetric model. Because the three-dimensional characteristics near the nozzle corner are not modeled, the peak stresses at the nozzle corner are not accounted for accurately. Therefore, a generic three-dimensional model developed by Gilman and Rashid (Reference 6) is used to scale the pressure stress. The scaling factor for the pressure stress is given by the ratio of the peak pressure stress on the inside surface reported by Gilman and Rashid to the peak pressure stress on the inside surface from the finite element model used in this report. The peak pressure stress of the finite element model was   , while the peak pressure

Table 5-1

STEADY-STATE SURFACE STRESSES TO
CHOOSE MAXIMUM COMBINED STRESSES

Figure 5-1. Feedwater Nozzle - FitzPatrick Location
of Maximum Surface Stresses

stress reported by Gilman and Rashid is 44,600 psi. This resulted in a scaling factor of   . The scaled peak pressure stress on the inside surface is shown in Figure 5-1.

The combined thermal and scaled peak pressure stresses were examined to determine the area where the combined peak stress on the inside surface occurs, as shown in Table 5-1. The combined stresses at the cross section associated with the combined peak stress (see Table 5-2, and cross section B-B on Figure 5-1) were used to calculate crack growth.

Table 5-2

STEADY-STATE STRESSES AT CROSS SECTION B-B

6. CRACK GROWTH ANALYSIS

6.1 STRESS INTENSITY FACTOR CALCULATIONS

Stress intensity factors are determined using solutions for standard stress distributions (e.g., constant, linear, quadratic, and cubic variations) and applying the superposition principle. The stress intensity solution for these unit load cases is expressed in terms of the crack length and appropriate magnification factors for the specific crack geometry (Figure 6-1). The stress intensity for an arbitrary stress distribution can then be obtained by fitting a third-order polynomial of the form:

$$\sigma = A_0 + A_1 X + A_2 X^2 + A_3 X^3$$

and applying the principle of superposition. Once the curve fit parameters A_0, A_1, A_2, and A_3 are known, the stress intensity factor can be determined as a function of crack depth using the equations in Figure 6-1.

Magnification factors for several common two-dimensional geometries are available in References 7 and 8. For the feedwater nozzle, a set of three-dimensional magnification factors is presented in Reference 1. As illustrated in Figure 6-1, the nozzle corner factors were obtained by averaging the magnification factors developed for circular surface crack geometries in half and quarter spaces. This expression (labeled FUN 11) was used to calculate stress intensity factors in the fracture mechanics evaluation which follows.

The pressure and thermal stress distributions were fit to third-order polynomials using a standard least squares procedure. Overall accuracy of the polynomial representations is considered more than adequate.
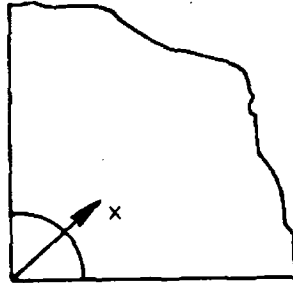
Substituting these polynomial coefficients (A_0, A_1, A_2, and A_3) into the FUN 11 stress intensity factor expression of Figure 6-1 leads to the stress intensity factor versus crack depth data shown in Figures 6-2 and 6-3.
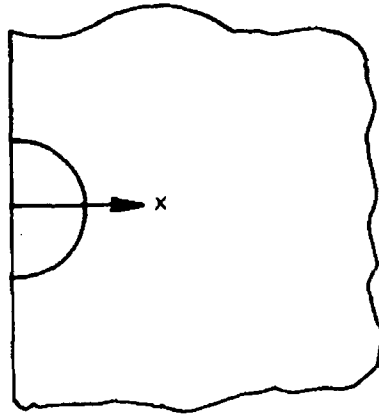
FUN 9 — SEMI-CIRCULAR CRACK IN HALF-SPACE

$$K_I = \sqrt{\pi a} \; [0.688 \, A_o + 0.522 \, (2a/\pi) \, A_1 + 0.434 \, (a^2/2) \, A_2 + 0.377 \, (4a^3/3\pi) \, A_3]$$

FUN 10 — QUARTER-CIRCULAR CRACK IN QUARTER-SPACE

$$K_I = \sqrt{\pi a} \; [0.723 \, A_o + 0.551 \, (2a/\pi) \, A_1 + 0.462 \, (a^2/2) \, A_2 + 0.408 \, (4a^3/3\pi) \, A_3]$$
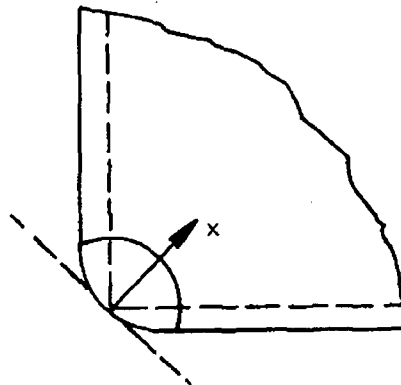
FUN 11 — SIMULATED 3-D NOZZLE CORNER CRACK

$$K_I = \sqrt{\pi a} \; [0.706 \, A_o + 0.537 \, (2a/\pi) \, A_1 + 0.448 \, (a^2/2) \, A_2 + 0.393 \, (4a^3/3\pi) \, A_3]$$

Figure 6-1.   Boundary Integral Equation/Influence Function
Magnification Factors for BWR Feedwater Nozzle

Figure 6-2. Stress Intensity Factor versus Crack Depth (Thermal Stresses)

Figure 6-3.   Stress Intensity Factor versus Crack Depth (Pressure Stresses)

· 6.2 CRACK GROWTH DATA

A compilation of the General Electric and Westinghouse fatigue crack
growth data for carbon and low alloy steels in reactor water environments
(References 9, 10) is presented in Figure 6-4. This data was used extensively
in Reference 1 and is considered to be representative of actual reactor ser-
vice. From this, a best-fit curve was developed and used to explain problems
observed in the field. Comparisons between the field data and those calculated
using the best-fit curve resulted in good agreement. This best-fit curve is
defined as follows:

In addition, Figure 6-5 presents the fatigue crack growth data for low
alloy steel from Section XI of the ASME Code (Reference 11). The R-ratio
(K_{min}/K_{max}) dependence of this data is built-in by representing three cases:
(1) R-ratio less than 0.25, (2) R-ratio between 0.25 and 0.65, and (3) R-ratio
greater than 0.65, as shown in Figure 6-5.

For the purpose of this evaluation, both crack growth rate curves dis-
cussed above are used to calculate the total crack propagation. The results
are then compared.

Figure 6-4. Carbon and Low-Alloy Steel Fatigue Crack Growth
Data in Water Reactor Environments
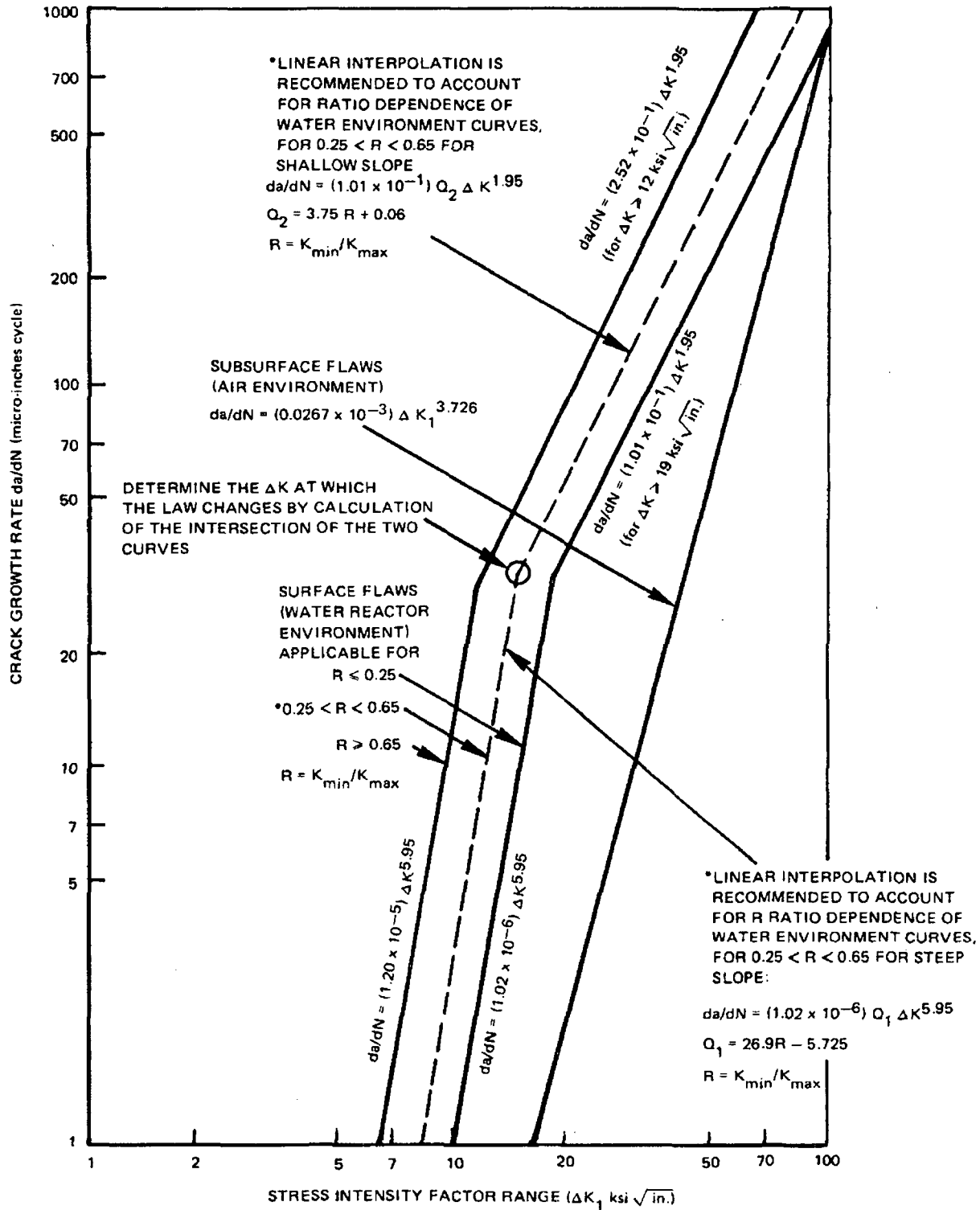
Figure 6-5. Reference Fatigue Crack Growth Curves for Carbon and Low Alloy Ferritic Steels

6.3 CRACK GROWTH EVALUATION

This analysis determined the crack growth from an initial size of
0.25 inch at time zero out to a time of 40 years. It is practical to equate
time zero in the analysis to the time at which the feedwater nozzles were
machined. The   low flow control are represented by the
thermal cycle definition shown in Figure 3-1. The feedwater nozzle experi--
enced   . The remaining
are represented by the startup/shutdown cycles described in Tables 3-1
through 3-3. Based on the measured events, there would be   of these
startup/shutdown events in the remaining   . This resulted in a total
of   over a 40-yr history of the plant following the machining of the
nozzles. All scram and shutdown events were assumed to have the same thermal
cycling history as the startup event.

The procedure for calculating the crack propagation follows. For each
cycle, the maximum and minimum stress and the number of occurrences were cal-
culated. From this, the stress intensity factor range and corresponding
R-ratio were calculated for the cycle being analyzed. Using this and the
selected crack growth relationship, the incremental crack growth was calcu-
lated for that event. The crack depth was updated and the procedure repeated.
This continued for every cycle until the entire life was analyzed.

7. RESULTS AND CONCLUSIONS

Figure 7-1. Crack Depth versus Number of Cycles,
RWCU Injection Line (Hot Nozzle)

Figure 7-2. Crack Depth versus Number of Cycles,
Non-RWCU Injection Line (Cold Nozzle)

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